



Refraction, Aliasing, and the Absence of Motion Reversals in Peripheral Vision

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Reversals in perceived direction of motion of a grating when its spatial frequency exceeds half that of the sampling mosaic provide a potential tool for estimating sampling frequency in peripheral retina. We used two-alternative forced-choice tasks to measure performance of three observers detecting or discriminating direction of motion of high contrast horizontal or vertical sinusoidal luminance gratings presented either 20 or 40 deg from the fovea along the horizontal meridian. A foveal target at a comfortable viewing distance aided fixation and accommodation. A Maxwellian view optometer with 3 mm artificial pupil was used to correct the refraction of the peripheral grating, which was presented in a circular patch, 1.8 deg in diameter, in a surround of similar colour and mean luminance ($47.5 \text{ cd} \cdot \text{m}^{-2}$). The refractive correction at each eccentricity was measured by recording the aerial image of a point after a double pass through the eye. The highest frequency which can reliably be detected (7–14 c/deg at 20 deg, 5.5–7.5 c/deg at 40 deg) depends critically on refraction. Refraction differs by up to 5 D from the fovea to periphery, and by up to 6 D from horizontal to vertical. Direction discrimination performance shows no consistent reversals, and depends less on refraction. It falls to chance at frequencies as low as one-third of the highest that can be detected. Gratings which can be detected but whose direction of motion cannot be discriminated appear as irregular speckle patterns whose direction of motion varies from trial to trial. The absence of motion reversals may reflect irregularity of sampling, and suggests that reversals are not a simple tool for studying sampling in peripheral vision.

Peripheral vision Refraction Aliasing Astigmatism Motion perception Motion reversal

INTRODUCTION

Sampling and aliasing

The first stage in the processing of the retinal image involves its conversion from a continuous distribution of illuminance into a set of discrete samples, the signals in the photoreceptors. This sampling process has potentially important effects on visual processing because any one set of samples could be produced by several different images, which are referred to as “aliases” of each other. This raises a problem of ambiguity which could, in principle, cause the visual system to misinterpret the image. The misinterpretations of the image associated with aliases are an important potential tool for studying the sampling processes both at the photoreceptor level and at subsequent levels of the visual pathway (Williams, 1985, 1992).

In the case of regular one-dimensional sampling, the

different aliases occupy different frequency bands whose width is given by the *Nyquist frequency*, which is half the sampling frequency. Within each frequency band there is only one possible alias, so if the image and its reconstruction can be restricted to the same band of frequencies, the problem of misinterpretation can be avoided. It seems that this is the situation in the human eye in the centre of the visual field. The optics form a low-pass filter, which restricts the retinal image to a band of frequencies (Artal & Navarro, 1994; Santamaría, Artal & Bescós, 1987) which are (just) within the bandwidth of the foveal cone mosaic (Curcio, Sloan, Kalina & Hendrickson, 1990). However laser interference fringes can be used to bypass the optical filter (Campbell & Green, 1965; Westheimer, 1960) and has been used to good effect to study the details of aliasing in the fovea. Images of high spatial frequency stationary gratings appear as wavy patterns of “zebra stripes” (Williams, 1985, 1992). These are the result of the visual system’s incorrect assumption that the image giving rise to the samples falls within the lowest band limited by the sampling frequency of the cone mosaic. More quantitative information about sampling can be obtained from the phenomenon of motion reversal, which is caused by the fact that the low frequency aliases of a high spatial

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frequency grating may move in the opposite direction to the original image (Coletta & Williams, 1987; Coletta, Williams & Tiana, 1990) see Fig. 1.

Outside the fovea aliasing has been widely studied using interference fringes (Coletta & Williams, 1987; Coletta *et al.*, 1990; Thibos, Cheney & Walsh, 1987a; Thibos, Walsh & Cheney, 1987b), however, our aim is to study aliasing in natural vision. The density of photoreceptors decreases rapidly with eccentricity, while

the eye's off-axis image quality deteriorates only slightly, leaving the periphery less protected against aliasing phenomena than the fovea (Navarro, Artal & Williams, 1993). Indeed aliasing in parafoveal vision can appear as a failure to discriminate orientation (Smith & Cass, 1987), and in the periphery it may appear as a reversal in direction of motion (Anderson & Hess, 1990). However, in peripheral vision, aliasing in natural vision appears to show a great deal of variability between

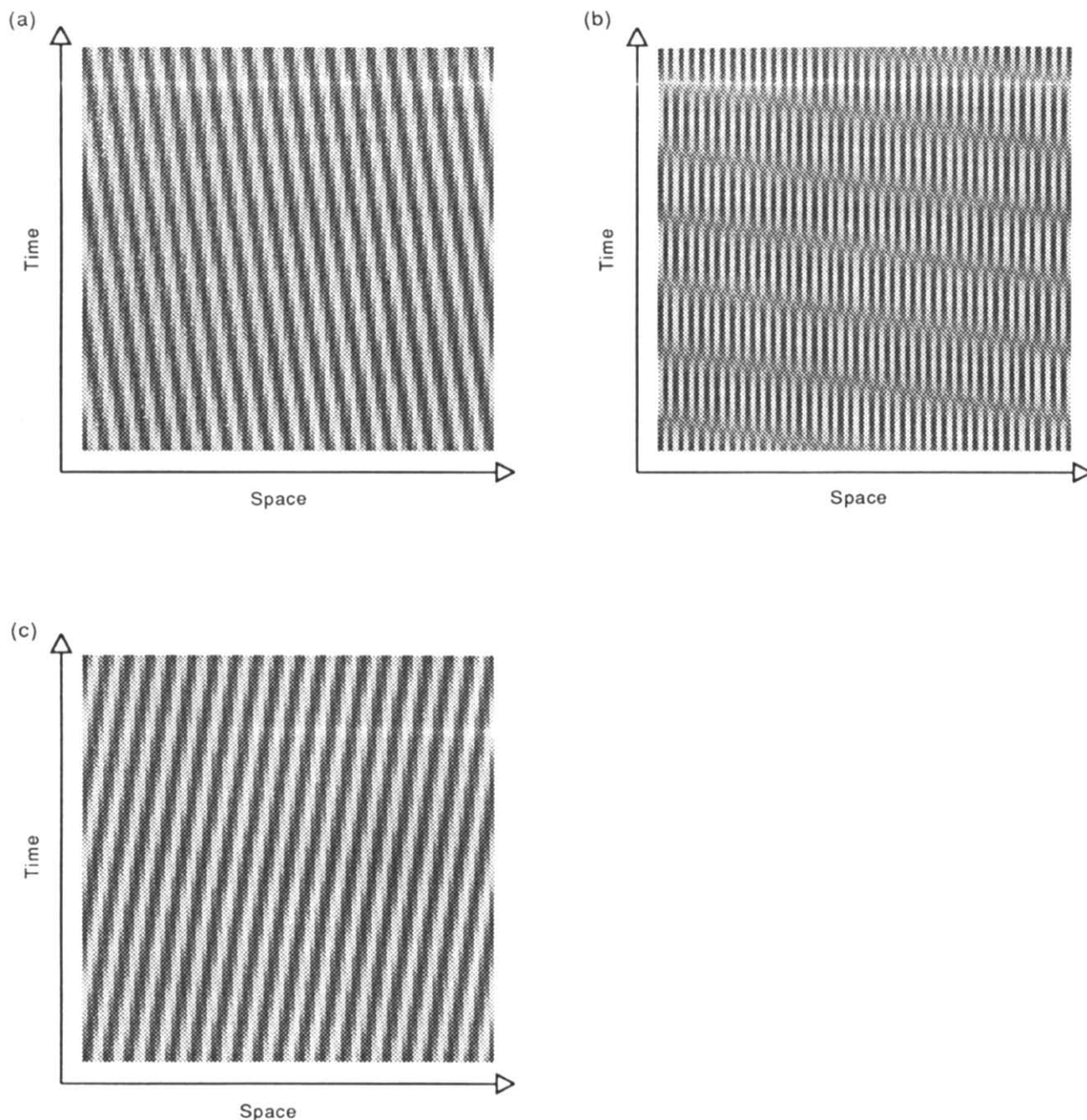


FIGURE 1. Illustration of the effect of spatial sampling on perceived direction of motion. (a) A space-time plot of a sampled, leftward-moving sinusoidal grating. The horizontal axis represents position; the vertical axis represents time. The frequency of the grating is 20 c/frame, and there are 80 samples on the horizontal axis. Thus the spatial frequency of the grating is much lower than the bandwidth limit imposed by the sampling frequency (40 samples per frame), and its motion is represented veridically in the sense that the lines in the space-time plot slope to the left, indicating leftward motion (Adelson & Bergen, 1985). (b) The spatial frequency of the grating has been increased to 40 c/frame. The direction of motion is indeterminate. (c) The spatial frequency of the grating has been increased to 60 c/frame. Sampling produces an alias of 20 c/frame moving in the opposite direction.

observers, and between orientations (Anderson, Drasdo & Thompson, 1995). One reason for this may be that to obtain good image quality in the periphery careful correction of refractive errors is necessary.

Refraction

It is well established that astigmatism can be quite marked in the periphery even in emmetropic eyes (Ferre & Rand, 1933; Ferre, Rand & Hardy, 1931; Lotmar & Lotmar, 1974). Recent objective measurements of image quality show that it is the main monochromatic aberration (Artal, Navarro, Brainard, Galvin & Williams, 1992; Navarro *et al.*, 1993) with typical values as large as 4–6 D for 40 deg of retinal eccentricity. With appropriate spherical refraction in the periphery, the spread of the retinal images in the best focus position for gratings of a particular orientation can remain practically constant across the whole retina. This implies that the actual optical resolution of the eye for gratings of particular orientations will be practically as good in the periphery as in the fovea, provided that the refractive correction is appropriate for the retinal location and orientation of the stimulus. On the other hand, if the correction is appropriate for the fovea, peripheral refractive errors may reduce the contrast of the retinal image avoiding aliasing artifacts (Galvin & Williams, 1992). Consequently, in order to study aliasing in natural vision in peripheral retina it is important to measure and to apply the appropriate correction.

Aim of this study

The main aim of the work reported here was to establish the best possible conditions for observing motion reversals in natural vision, with the aim of using them as a tool to study sampling. First we measured the optimal refraction of all our observers' eyes for horizontal and vertical targets in the fovea and in three peripheral locations. We then measured detection and direction of motion discrimination performance using sinusoidal gratings of high contrast and spatial frequency presented at the same eccentricities at which we had previously made optical measurements.

METHODS

Objective refraction

Objective refraction of subjects in the fovea and periphery was achieved by real time monitoring of the image of a point test after reflection in the retina. The system is based on that proposed by Arnulf, Santamaria and Bescós (1981) for the dynamic recording of retinal images, and has been used more recently for objective refraction and centering in experiments to measure retinal image quality (Artal, Ferro, Miranda & Navarro, 1993; Artal & Navarro, 1994).

Optical setup. Figure 2 shows the diagram of the experimental system. The beam coming from a He-Ne laser (nominal power 10 mW) first passes through a neutral density filter (DF), ND = 0.2–1.6, to attenuate

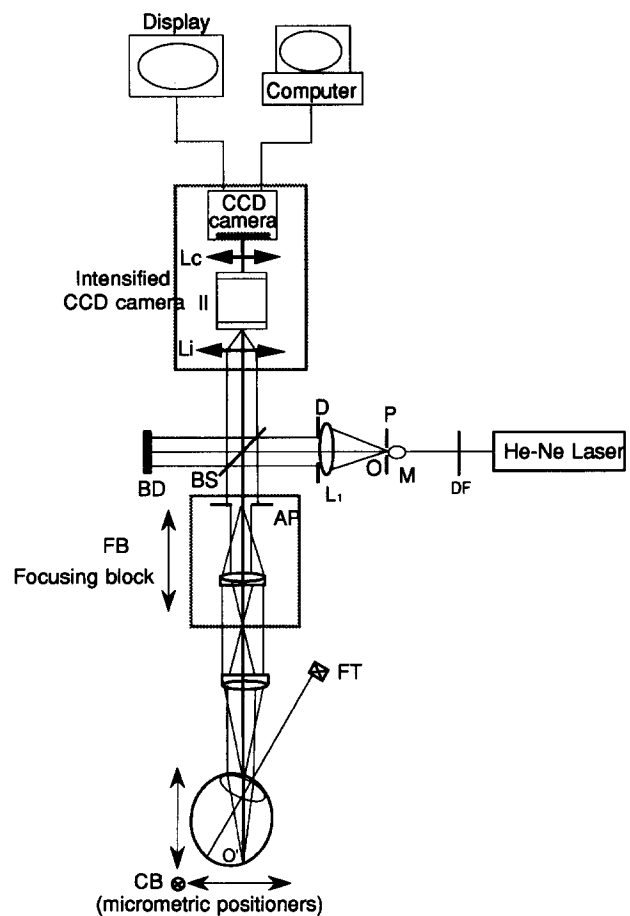


FIGURE 2. Schematic diagram of the optical system used for measuring refraction. (ND = 0.2–1.6); M, microscope objective; P, pinhole; AP, 4 mm spot; FB, focusing block; CB, centring micrometric stages; BS, pellicle beam splitter; BD, light trap; L₁, L₂, L₃, achromatic lenses; L_i, L_c, camera lenses; II, image intensifier; FT, fixation test.

and adjust the incident light intensity to the optimum range of the recording system. The beam is spatially filtered by a 40× microscope objective (M), and a 10 μm pinhole (P), which acts as the point object (O). The emerging beam is collimated by the lens L₁ ($f' = 200$ mm); about 8% of the light is reflected towards the eye by a pellicle beam splitter (BS), the light transmitted is removed from the beam path using a light trap (BD). Before entering the eye the beam passes through an afocal system, consisting of two equal achromatic lenses L₂ and L₃ ($f' = 120$ mm). The artificial pupil AP is imaged in the subject's pupil plane by the lenses L₂ and L₃ independent of their relative position. The subject's refractive state can be continuously modified by moving the focusing block (FB) backward and forward. The eye forms the image of the point O on the retina O' and a small fraction of the light is reflected back, passing again through the optical media of the eye (second pass), lenses L₂ and L₃ and the beam splitter. The camera lens L_i (105 mm focal length) forms the aerial retinal image on an image intensifier (II), which is coupled to a CCD camera by the lens L_c. This image intensifier recording system allows monitoring of the retinal aerial image of a point source in real time comfortably and under safe conditions for the subject.

The average irradiance in the pupil plane is $3.5 \mu\text{w}/\text{cm}^2$, several orders of magnitude below the maximum limit permitted by safety standards (Sloney & Wolbarsht, 1980). A frame grabber (Matrox MVP-AT) also permits the digitising of the image if desired.

Experimental procedure. Objective measurements of the refraction were obtained in three subjects. A foveal fixation test (FT) was placed at a comfortable viewing distance in different locations for 15, 20 and 40 deg retinal eccentricities in the horizontal meridian. The measurements were carried out with monochromatic light (632 nm) in subjects under normal viewing conditions (without paralysing accommodation and natural pupil). The subject's head was fixed by a bite bar mounted on micrometric positioners (CB) which were used to centre the observer's eye with respect to the 3 mm artificial pupil. The aperture (AP) was rotated to the appropriate angle and orientation for each eccentric location. The refractive state was determined by moving the focusing block (FB), while the experimenter monitored the image, looking for the position where the aerial retinal image had the appropriate shape and the minimum spread. Series of five measurements were taken for three different positions of "best" focus: the smallest circle of confusion; the sharpest horizontal profile; and the sharpest vertical profile.

Psychophysics

Optical setup. The subject fixated a small white spot, placed at his preferred fixation distance, and viewed the grating target through a Maxwellian view optometer with a 3 mm exit pupil imaged in his pupil, and a field of approx. 7 deg, as illustrated in Fig. 3.* This enabled us to vary the focal distance and eccentricity of the grating target while allowing the subject to maintain his accommodation using the foveal test. In preliminary experiments we found that the dark surround to the peripheral stimulus made it difficult to concentrate on the peripheral stimulus without making eye-movements towards it. We were able to improve both the comfort, and the performance of the observers by painting the field stop of the Maxwellian view flat white, and illuminating it with white light so that it approximately matched the video monitor in brightness and colour.

The focus of the optometer was adjusted for each observer and for each retinal location and orientation. Initial settings were made with reference to the optical measurements which had been carried out previously (except in the case of observer AMD's left eye). However, the refraction measurements had been made with red light, and the psychophysical measurements were done with white light, which would be expected to

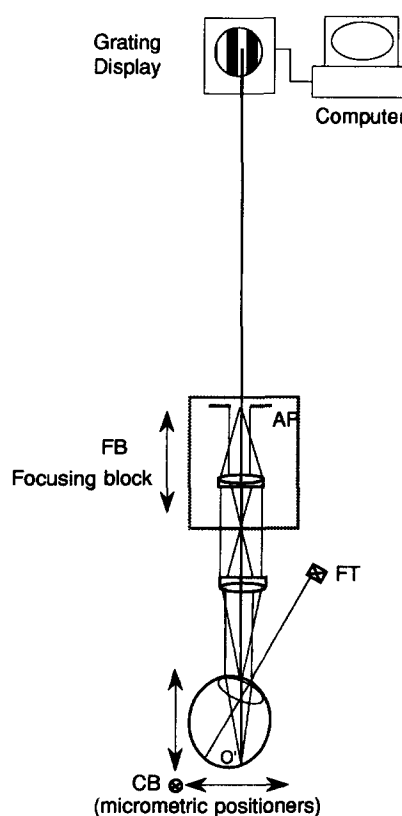


FIGURE 3. Schematic diagram of the optical system used for psychophysical measurements. The difference from the system used for measurements of refraction is the use of a CRT monitor (grating display) as a source, and the removal of the apparatus for image intensification.

produce a small offset in the position of best focus. Accordingly, a systematic search was made to find the refractive correction that resulted in the best performance in detecting a grating of high spatial frequency.

Observers. The three observers used were the three authors. All had normal vision when corrected. Observers EC and PA are both myopic in the fovea, and used a fixation target at a comfortable viewing distance and no external refractive correction except for that provided by the optometer. Observer AMD is approx. 2 D hypermetropic and slightly astigmatic, and made the optical measurements under two different conditions. One set of measurements was made using an auxiliary external 2 D lens to focus the test, and the other was made wearing his normal disposable soft contact lens. The two sets of measurements were almost identical except for an offset caused by the fact that, when the auxiliary lens was used, the optometer also corrected the hypermetropia. Psychophysical measurements were made with the contact lens only.

Stimuli. The stimuli were high contrast grating patterns presented by a computer (IBM AT compatible) using a framestore graphics card (Cambridge Research Systems VSG 2-1) on a video monitor (Mitsubishi HL7955). The gratings were either horizontal or vertical, had a sinusoidal luminance profile, and were presented within a circular aperture for 1 sec duration, with a Gaussian temporal envelope of $\sigma = 0.2$ sec. During their

*With the optical arrangement shown in Fig. 3, movements of the focusing block to change the refractive correction also induce small changes in magnification, with consequent changes in spatial frequency. The largest change in our study was less than 10% and was always the same for detection and discrimination tasks. Consequently these changes have been ignored, and the spatial frequencies in any one graph could be in error by up to 10%.

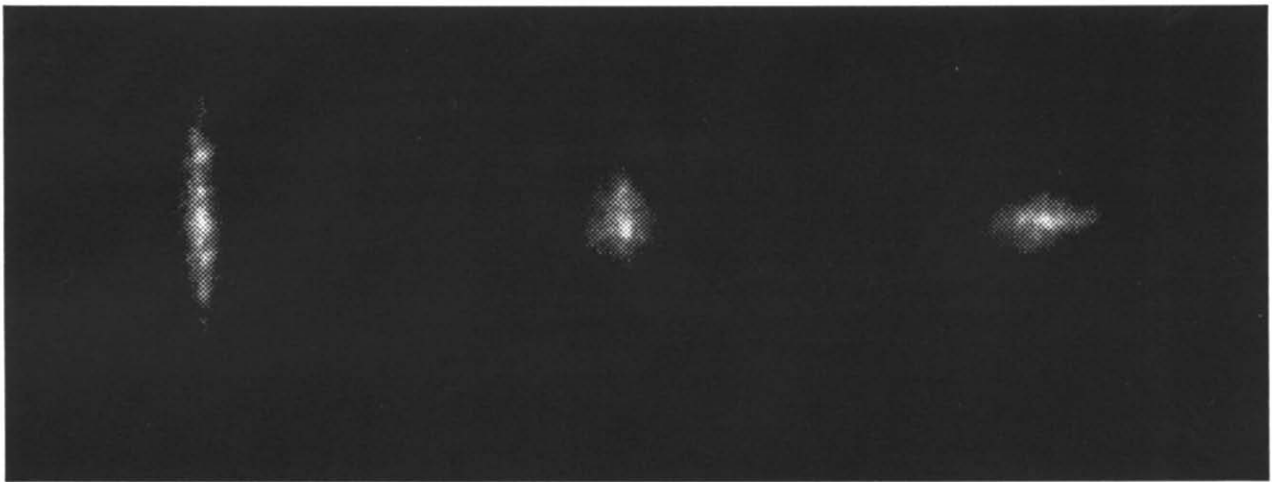


FIGURE 4. Images of a point source at 40 deg eccentricity in temporal retina obtained from AMD's right eye. The three images were obtained at the best focus for the horizontal axis (left), the best overall focus (centre) and the best focus for the vertical axis (right). Note the display has a 6:5 aspect ratio which magnifies the vertical axis.

presentation they moved continuously with a temporal frequency of 10 Hz. The general procedure for displaying and moving the gratings has been described before (Derrington & Suero, 1991). The three guns of the colour monitor were wired in parallel, so that the grating patterns varied in luminance but not in chromaticity. The display frame rate was 120 Hz, and its mean luminance was $47.5 \text{ cd} \cdot \text{m}^{-2}$.

Experimental procedure. A two-alternative temporal forced-choice (2AFC) paradigm was used to measure performance in detecting or discriminating the direction of motion of grating patterns. In direction-discrimination experiments using vertical gratings the procedure was as follows. On each trial, a grating was presented twice. Each presentation was signalled by a burst of audible noise. During the first presentation the direction of motion was selected at random, each direction being chosen with probability 0.5, and during the second presentation the grating moved in the opposite direction. The observer's task was to indicate the presentation on which the grating had moved leftwards. On trials using horizontal gratings the procedure was the same, except that the gratings moved vertically upwards or downwards, and the task was to select the presentation in which the grating had moved upwards. The observer was given no feedback as to the correctness of his response on any individual trial.

In detection experiments the procedure we adopted initially was to present a grating in one of the presentation intervals and a blank screen in the other. However we found that with the high contrast gratings we were using (contrast 1.0) there was a change in the mean luminance of the screen of about 0.5% when the grating was presented, which was sufficient to allow the observer to detect the grating without being aware of any spatial pattern. To prevent the observer using the change in mean luminance as a cue, we replaced the blank field with a grating of high spatial frequency (20 c/deg) which produced the same change in mean luminance, but no detectable spatial pattern.

Each block of trials consisted of 25 trials with a set of gratings of four or five different spatial frequencies. On each trial the frequency to be used was selected at random, with the constraint that no frequency would be used if another frequency in the set had been used for fewer trials. Trials were self paced, and observers were encouraged to take rests whenever they found the bite-bar uncomfortable.

RESULTS AND DISCUSSION

Optics

The optical measurements showed, in agreement with Navarro *et al* (1993), that all the observers' eyes were very astigmatic at 40 deg eccentricity. Figure 4 illustrates this general point with three examples of the image of a point source at 40 deg eccentricity. The different images were obtained with different amounts of (spherical) refractive correction, corresponding to three different criteria for optimising the focus. The image on the left was obtained with a correction of -2.5 D , which produced the sharpest horizontal profile; the image on the right was obtained with a correction of 3.9 D , which produced the sharpest vertical profile; and the image in the centre was obtained using a correction of 0.2 D , which produced the smallest circle of least confusion. The large difference between the corrections that give optimal focus for vertical and horizontal orientation indicates clearly that psychophysical measurements in this part of the retina should use different corrections for different orientations.

The astigmatism illustrated in Fig. 4 was also apparent at other eccentricities, and in other observers. Figure 5(a) shows a graph of the refractive corrections for other eccentricities in the same eye. The data show three important features, that were also found in the other two observers. First, the astigmatism is greatest at 40 deg eccentricity, amounting to a difference of over 6 D between the best horizontal focus and the best vertical focus for this eye. The differences found in the other two

observers were of the same order of magnitude, being 2.3 D in observer EC and 4.3 D in observer PA. Second, the astigmatism tends to decrease at lower eccentricities. At 20 deg observer AMD shows a difference of 2.1 D between horizontal and vertical focus, EC showed no difference, and PA showed a difference of 2.2 D. The third feature of the data is that it is impossible to predict the best refractive correction in the periphery from the best refractive correction in the fovea. Accordingly we felt it was essential for the success of the psychophysical work to tailor the refractive correction to the stimulus conditions for each eye.

One important question that arises from Fig. 5(a), which was obtained with the subject wearing his normal contact lens correction, is whether the contact lens affects the measurements, and whether the measure-

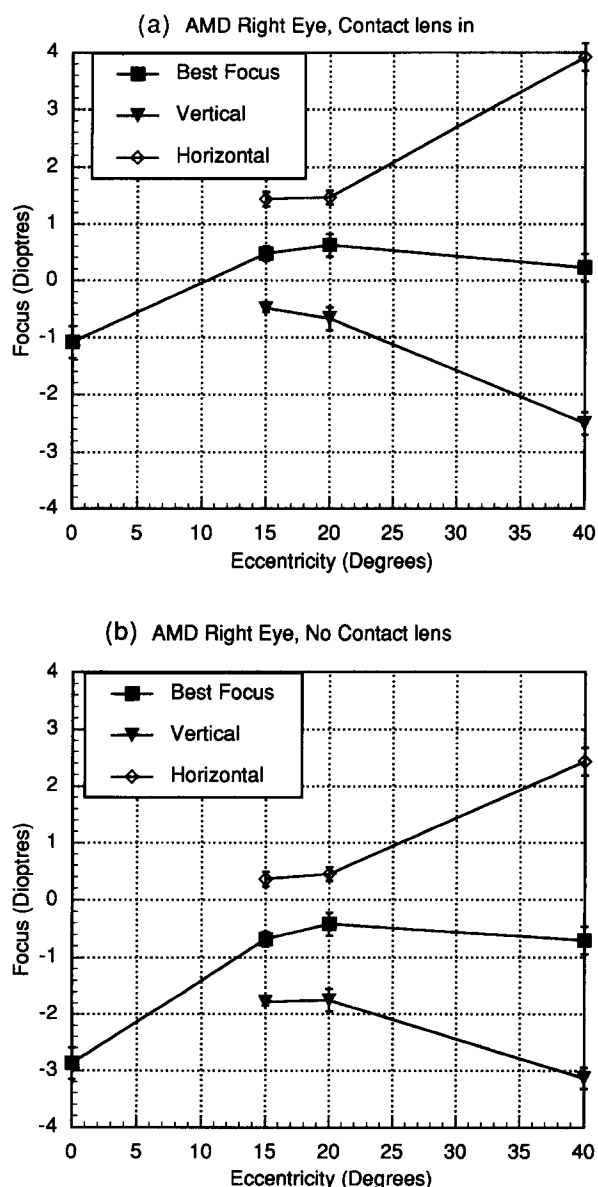


FIGURE 5. (a) Refractive corrections for best overall focus, sharpest horizontal profile, and sharpest vertical profile of the image of a point at different eccentricities along the horizontal meridian in temporal retina of observer AMD. Error bars show the SEM of 10 estimates. (b) The same measurements made on a different day, and without the contact lens.

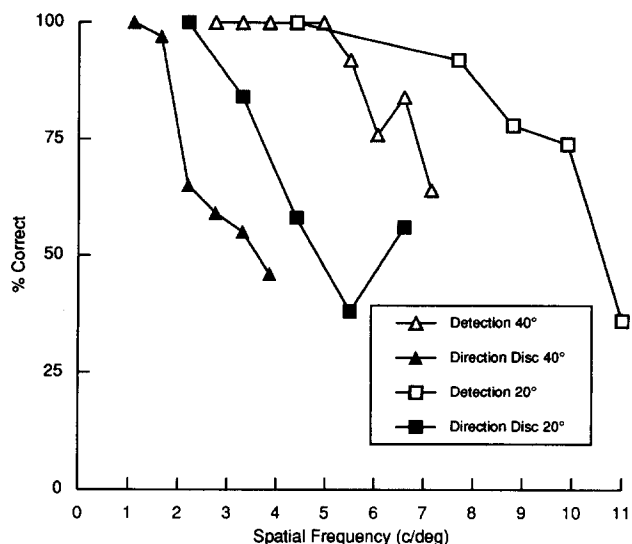


FIGURE 6. Performance in detection and direction-discrimination tasks using vertical gratings presented in a circular field 1.8 deg diameter at eccentricities of 20 and 40 deg in nasal visual field. Each point is the percentage of trials on which the observer was correct, estimated from two sets of 25 trials. Grating contrast was 1.0.

ments themselves, which show some variability, would be stable over time. Figure 5(b) shows the same measurements as Fig. 4(a) repeated on a different day, and without the contact lens. The graphs are very similar to those of Fig. 5(a), except for a general shift of about 2 D. This shift presumably reflects the fact that the optometer was providing the correction normally provided by the contact lens. Thus the main features of the data appear to be stable, and appear not to be affected by the contact lens. Accordingly, for psychophysical data collection this observer wore his contact lens.

Psychophysics

General differences between detection and discrimination. The main features of the psychophysical data were similar for all observers, for both horizontal and vertical orientations, and for both retinal eccentricities. They can be seen in Fig. 6, which shows detection and discrimination performance of observer PA plotted against spatial frequency. The stimuli used were vertical gratings presented at eccentricities of 20 or 40 deg. The two main features, that are common to all our sets of data, are as follows. First, there are no clear examples of reversals in direction of motion at the retinal eccentricities and with the viewing conditions we have used: performance in both tasks falls monotonically with spatial frequency. Second, in the detection task performance remains good at higher spatial frequencies than it does in the direction-discrimination task.

In view of the original aims of this study, the lack of reversals is frustrating, and we will return to it in the discussion section. However, it is an absolutely consistent feature of the data we have obtained exploring both nasal and temporal retina using vertical and horizontal gratings in three observers. It is quite clear that gratings of the highest spatial frequencies that are detectable are detected as aliases—they do not look like gratings at all,

but more like moving or shimmering speckle patterns, confirming earlier observations made using interference fringes (Thibos *et al.*, 1987a, b). Thus the clearest evidence for aliasing in our data, which again is a consistent feature for all observers for both orientations and for both eccentricities, is the finding that detection performance is better than discrimination performance. This finding is consistent with the expectation that those gratings would be detected as aliases, but indicates that the aliases do not have a consistent direction of motion.

Several times we found very low proportions of correct responses, suggestive of reversed motion, when the proportion was estimated from only 25 trials, but the proportion always rose when we collected more data at the same spatial frequency. In fact Fig. 6 contains our most promising example of a reversal in direction discrimination. At a spatial frequency of 5.5 c/deg performance at 20 deg eccentricity is only 38% correct measured over 50 trials. Although such a low performance level is statistically unlikely, it is not surprising that in the large amount of data we have collected one or two such points should arise. Indeed in the same figure the detection performance at a spatial frequency of 11 c/deg at 20 deg eccentricity provides another example: performance is 36% correct.

Effect of increasing stimulus size. The results in Fig. 6 were obtained using stimuli confined to a small circular patch of the display, 1.8 deg in diameter. We had decided to use such a small stimulus because the aliased grating percepts appeared spatially irregular, and we thought that they might also be inhomogeneous, consisting effectively of several aliases, each behaving differently. One strategy for dealing with this situation is to use a small field, so that by minimizing any spatial inhomogeneity consistent behaviour of the alias, and in particular a consistent apparent direction of motion, would be more likely to emerge. However, another possibility in a

situation where there are multiple aliases, is to use a larger stimulus area, so that by averaging over a larger area one might obtain a less noisy local average, and thus obtain consistent behaviour. Furthermore, previous experiments in which consistent reversals of motion were obtained with natural viewing (Anderson & Hess, 1990) used larger stimuli. For this reason we repeated our measurements of direction of motion discrimination using the largest stimulus we could present.

Figure 7 shows direction discrimination for two observers using larger stimuli, 6.5 or 7.5 deg in diameter. The only difference between these results and those obtained with smaller (1.8 deg) stimuli, shown in Fig. 6, is that performance is slightly better with the larger fields. There is no hint of a reversal in performance, although once again there was clear evidence of aliasing: acuities estimated using detection tasks were better than acuities estimated using direction discrimination tasks (not plotted). In other words, there is a range of spatial frequencies where gratings can be detected but their direction of motion cannot be discriminated.

GENERAL DISCUSSION

There are three points that emerge from our data. The first two are not novel, they simply clarify and confirm earlier work, highlighting the importance of refraction for estimating the capabilities of vision in peripheral visual field and confirming the existence of aliasing in peripheral retina. However our third finding is novel: we fail to find motion reversals under natural viewing conditions.

Refraction

Our measurements of refraction confirm Navarro *et al.* (1993) in showing that there is substantial astigmatism in peripheral retina, and that for a given orientation, the difference between the best refraction in the fovea and the best refraction in the periphery can amount to several dioptres. In our psychophysical confirmations of the refractive correction we found that, even at 40 deg eccentricity, performance in detecting gratings of frequencies close to the maximum detectable frequency was impaired by refractive errors of <1 D. Moreover the highest spatial frequencies at which our subjects can detect gratings and discriminate their direction of motion are higher than those found by Anderson, Mullen and Hess (1991) who did not correct peripheral errors in refraction. We found that the effect of refraction on performance was more important in detection tasks using spatial frequencies above the limit for discrimination of direction of motion. This is in agreement with Anderson *et al.* (1995) who found that correction of peripheral refractive errors improved performance in detection tasks.

There is an apparent disagreement between our observations on the importance of refraction and the results of Millodot, Johnson, Lamont and Leibowitz (1975), who found that correction of refraction had little or no

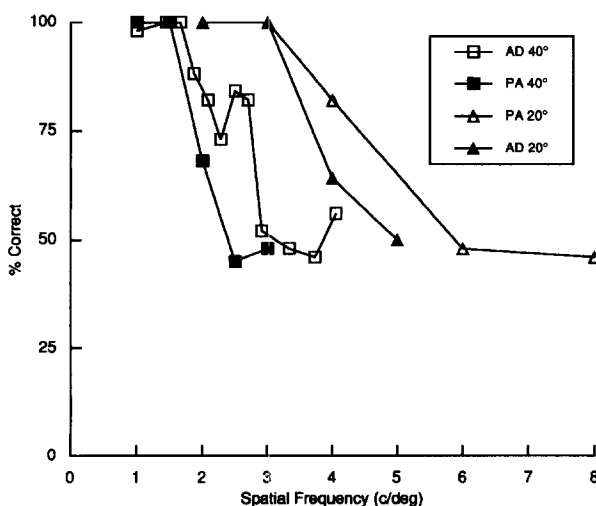


FIGURE 7. Direction of motion discrimination of two observers using large stimuli. Performance (% correct) is plotted against spatial frequency. Stimulus eccentricities were 20 deg or 40 deg in nasal visual field. Stimuli were presented within a circular patch of diameter 6.5 deg. AMD's data at 20 deg were obtained using a stimulus 7.5 deg diameter.

effect on peripheral visual acuity, measured using a subjective task in which observers reported whether they could resolve the lines in a horizontal grating. However, the disagreement about the importance of refractive correction may be more apparent than real for two reasons. The first is that most of the refractive errors of Millodot *et al.*'s (1975) study were rather small, and in the one case where there was a large error, they noted that correction of the refractive error improved performance. The second reason is that Millodot *et al.* (1975) measured the highest frequency at which their observers reported that they could resolve the bars in the grating. This is more similar to our direction-discrimination task than to our detection task, and we also found that modest refractive errors had little effect on performance at the spatial frequencies where direction-discrimination was possible.

Aliasing

A difference between detection and direction-discrimination tasks in the position of the high frequency limit of the psychometric functions relating performance to spatial frequency is not itself evidence for aliasing. Such differences have in the past been attributed to differences in spatial resolution between mechanisms that analyze spatial structure and those that analyse motion (Murray, MacCana & Kulikowski, 1983). However there are clear examples in our data where the difference between the spatial frequency limit for direction discrimination and that for detection is more than a factor of 2, which far exceeds the difference required to specify phase or direction of motion. Furthermore, the subjective appearance of the gratings which, even when their direction of motion can just be discriminated appear as fields of spatial noise, is consistent with the existence of aliasing (Thibos *et al.*, 1987a, b). It indicates that there is a range of spatial frequencies where the grating elicits a spatially varying signal, which contains insufficient samples for the reconstruction of the original grating.

Our results are consistent with the observation of aliasing in natural vision using an orientation discrimination task. Smith and Cass (1987) tested orientation discrimination and detection of square-wave gratings at eccentricities of 4 and 7.5 deg, and found that orientation discrimination fell to chance at lower spatial frequencies than did direction discrimination. However the range of eccentricities tested by Smith and Cass (1987), did not overlap with the range we used. One problem in testing orientation discrimination at large eccentricities is that it requires astigmatism to be corrected by an appropriate cylindrical lens, so that both orientations in the discrimination task can be tested concurrently.

Absence of motion reversals

It is important to explain our failure to find motion reversals in aliased gratings, particularly with reference to the successes of other workers (Anderson *et al.*, 1995; Anderson & Hess, 1990; Coletta *et al.*, 1990). Before attempting to deal with our results obtained at eccen-

tricies of 20 and 40 deg we will consider the situation in parafoveal vision.

The cone mosaic is more regular closer to the fovea, and so the aliases of gratings are more regular, and more likely to have consistent reversed motion. However, nearer the fovea the cones are closer together, which requires one to use higher spatial frequencies which are not well transmitted by the optics. This is why we have not attempted to study aliasing in the parafovea. The optical transmission losses can be avoided by the use of laser interference fringes (Campbell & Green, 1965), which permits high contrast images to be generated at spatial frequencies that give a clear percept of reversed motion (Coletta *et al.*, 1990). Indeed the reversed motion generated by interference fringes is sufficiently robust that it has been demonstrated (4% correct responses in 50 trials) in near peripheral retina even in our observer AD.

At greater eccentricities, reversed motion, even with interference fringes, becomes less compelling, although even at very large eccentricities it is possible to measure reversals (Coletta *et al.*, 1990). Presumably this increasing difficulty results from increasing disorder in the cone mosaic. The effect of this would be that within any small area of the retina there would be multiple aliases, corresponding to the multiple sampling frequencies available locally, and that the different aliases would move in different directions. Indeed Yellott (1982) has suggested that disorder in the cone mosaic may be important in protecting the visual system from systematic errors caused by aliasing. The fact that we are unable to measure reversed motion even though it has been measured both using interference fringes (Coletta *et al.*, 1990), and in natural vision (Anderson & Hess, 1990) may suggest that our observers have rather more disordered retinas than others and are thus better protected against aliasing (Yellott, 1982). It is unlikely that they have worse optics, as detection and direction-discrimination acuities are both high. There is clearly a good deal of individual variation, particularly in peripheral retina (Coletta *et al.*, 1990, Fig. 12). The aliased gratings often elicited compelling sensations of motion, but these were never consistently reversed. Indeed at the highest frequencies at which their direction of motion could be distinguished correctly, the gratings no longer appeared as regular patterns of stripes, but as drifting patterns of speckled noise.

In conclusion we suggest that, although aliasing is apparent in peripheral visual field under natural viewing conditions, motion reversal is not a simple or reliable tool for revealing it.

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